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Radio-frequency Transducers and Algorithms for Determining the Volumetric Content of the Components of Emulsion and Stratified Flows

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Abstract: Radio-frequency transducers for obtaining primary information about parameters of the flows of mixes in pipelines are proposed. Sensors of transducers are resonators of a special construction, which do not create interference with the flow. The dependences of resonance frequency and amplitude of oscillations of resonators on the volumetric content of components of two- and three-component emulsions and stratified flows are obtained. On the basis of these dependences, algorithms for specific applications, such as measuring the mixes of gas-liquid flows, in particular "gas - oil - water", are developed.

1. INTRODUCTION

The need for determining the volumetric content of components in the pipeline arises in control systems of the composition of flows of mixes in oil outputs, in chemical production, in engine installations, in control systems of drains, in heat-transfer agents of nuclear reactors, and also in the systems of monitoring the ecological standards of discharges by industrial enterprises. For three-component mixes and in certain cases for two-component ones, at least two channels of primary information are required, which can be relatively easily obtained in the class of radio-frequency transducers. In the sensors of such transducers, the electromagnetic oscillations in the regime of resonance are excited, and it is possible to use resonance frequency, Q–factor and amplitude as the indirect volume measurements. Those sensors which do not interfere with the flow and do not change its structure, are preferable constructions of resonators, such as cavity resonator with the embedded dielectric faucet (type 1) (Wylie et al, 2006), and resonator on the basis of a locked conductor, distributed inside the dielectric tube (type 2) (Lunkin et al, 1999), with inside diameters equal to the pipeline diameter; resonator in the shape of a flexible dielectric tape with thin conductor distributed above the metal strip (type 3), fixed on the internal wall of the pipeline (Lunkin et al., 2007). Algorithms are determined by the physical properties of the components of a mix (dielectric constant and conductivity) and are established on the basis of the dependences of natural frequency, Q-factor of resonator and amplitude of the electromagnetic oscillations excited in it, with the agreement of the frequency of the exciting oscillator with natural frequency. Two models of the state of the controlled mix in the flow are examined – one in the form of emulsion, which is, in a broad sense, a dispersal system either of two or more not completely immiscible liquids, or of liquid (it can be two-component) and gas, and stratified mixes, whose components have clear boarders between them – situation, which usually occurs in non-pressure channels.

2. TWO-COMPONENT EMULSION FLOWS

Such flows are typical for gas-liquid mixes. If liquid is a dielectric medium, the resonance frequency of any of the types of resonators pointed out above can be accepted as the indirect value of measurement of the volumetric content of the mix components. This value can be also used for the liquid dielectric components of a mix. With a significant difference in the dielectric constants of components, high accuracy of measurement can be achieved. Problems may appear if one of the components has variable conductivity.

2.1 Emulsion of "dielectric - dielectric with variable conductivity" mix

This class of mixes includes "oil (petroleum products) - water with arbitrary degree of mineralization" mixes. Determination of the volumetric content of their components in the range of relative values of 0-1 for each component is an important and timely task. For the "transformer oil (o) - water (w)" mix, dependences of resonance frequency and amplitude of oscillations in type 2 resonator on the volumes of its components for different values of salinity are established using physics principals and application of experimental results.

Experimental installation includes the locked conduit, in which the centrifugal pump forms the mixture of transformer oil and water. The resonator in the form of the locked thin conductor is built in the conduit and distributed in a zigzag manner inside the dielectric tube, inserted in the metal housing. Electromagnetic oscillations in the resonator are excited from the generator of the tunable frequency of the spectrum analyzer (Vector Network Analyzer, ZVER) through the capacitive coupling with an arbitrary point of conductor. The moment of resonance is determined by the maximum voltage in the point of conductor that is opposite along diameter of the tube to that arbitrary point. This voltage spreads via the capacitive coupling to the detected entrance of the spectrum analyzer, where the values of resonance frequency, quality of resonator and amplitude of electromagnetic oscillations are registered on the monitor. The values are obtained by averaging of the results of repeated measurements. The temperature is maintained constant.

The image of these dependences together with the experimental values is illustrated by graphs in Fig.1 and Fig.2.

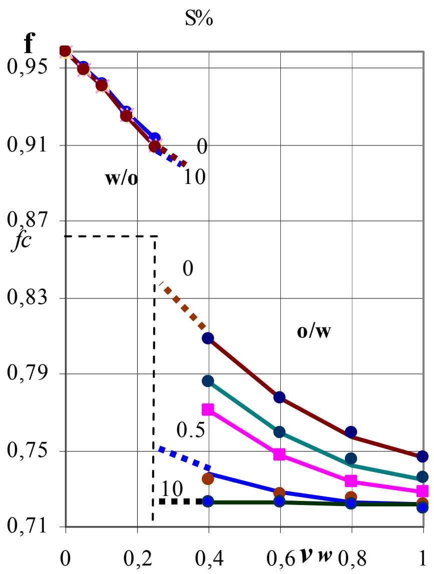

Fig. 1 Dependences of resonance frequency on water volume in “oil-water” mixes

For “w/o” emulsions resonance frequency as the informative parameter should be accepted, since it has high sensitivity to the water volumetric content and depends little on its salinity. It is possible to accept the amplitude of oscillations, but it depends substantially on the salinity. For emulsion of “o/w” type, the resonance frequency depends substantially on the salinity, but its informativeness remains only in the range of 0-0,5%. For the salinity of water, more than 0,5%, the sensitivity of resonance frequency to a change in the volume of water sharply decreases, which does not make it possible to obtain acceptable accuracy of measurement. In this range of salinity, amplitude has sensitivity sufficient for measurements. Let us note that resonance frequency values give the key to the type of emulsion, since frequency bands for different emulsions essentially differ.

The analysis of graphs makes it possible to formulate the algorithm of measurement in the following form:

$$v_w = \begin{cases} \varphi_1(f), \text{ if } \ f \leq f_c, \ S - any \\ \varphi_2(f), \text{ if } \ f \succ f_c, \ 0 \leq S \leq 0.2\% \\ \varphi_3(u), \text{ if } \ f \succ f_c, \ 0.2 \leq S \leq 0.5\% \\ \varphi_4(u), \text{ if } \ f \succ f_c, \ S \succ 0.5\% \end{cases}$$

$$v_o = 1 - v_w,$$

where v_w - relative volumes of oil and water, S - salinity in percent (grams of salt in 1 liter of water); $\varphi_1(f)$, $\varphi_2(f)$ - function, reverse to the functions, which describe the dependence of the standardized resonance frequency f on the relative volume of water v_w for “w/o” and “o/w” emulsions, correspondingly, in the range of salinity indicated; $\varphi_3(u), \varphi_4(u)$ is the same for the dependence of the standardized amplitude of oscillations u, f_c - middle of the jump of resonance frequency with the change of the type of emulsion. The obtained algorithm of measurement is applicable to petroleum-water mixes, since their electrical properties are similar to "petroleum products - water" mixes.

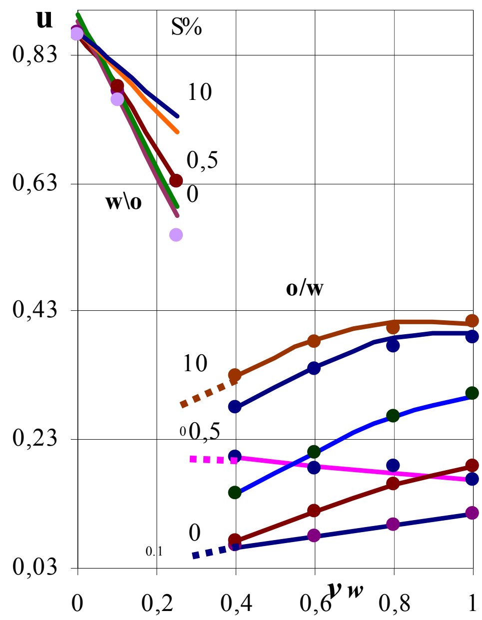

Fig. 2 Dependences of amplitude of oscillations on water volume in “oil – water” mixes

3. THREE-COMPONENT EMULSION FLOWS

There are many cases, in which one of the components of a mix is gas, and two others - immiscible liquids or liquid with solid particles. A priori, three values that describe the signal obtained from the resonator (resonance frequency, Q-factor, amplitude) make it possible to pose the problem of volumetric measuring of the components of such mixes. However, studies have shown that dependences of Q-factor and amplitude on volumes strongly correlate; therefore only one of them can be taken as the informative value.

3.1. "Gas - oil - water" type mix

Determination of volumes of the components of such a mix is important in gas- and oil pipelines. As follows from the graphs on Fig.1, 2, with the salinity of water *S>0.5%* the resonance frequency loses informativeness for emulsion of oil-in-water, and with low salinity - amplitude of oscillations for the same emulsion. Thus it is possible to consider the algorithms of measurement only for emulsions of the "oil and water into gas ((o,w)/g)", "gas and water into oil ((g,w)/o)" type, i.e. for emulsions, in which water with arbitrary salinity is in dispersed state. Using type 2 resonator for the above mentioned emulsions, the following functions of resonance frequency and amplitude oscillations have been obtained:

$$f = (1+(a_{f1}(1+a_{f2}e^{a_{f3}S})v_w+1) \cdot (\varepsilon_g v_g + k_{fo}\varepsilon_o v_o + k_{fw}\varepsilon_w v_w - 1))^{-1/2} \quad (1)$$

$$u = (1+k_u)/1+k_u(1+(a_{uw}+1) \cdot (\varepsilon_g v_g + k_{uo}\varepsilon_o v_o + k_{uw}\varepsilon_w v_w - 1)) \quad (2).$$

In (1) above, coefficients *a, k* with corresponding indexes are constant, while in (2) - they depend on *S*, and the functions for their description are based on experimental data and look like this:

$$\begin{aligned}&(a_{uw},k_{uw},k_{uo}) = (1+(a_{uw1},k_{uw1},k_{uo1})S)\\&/((a_{uw2},k_{uw2},k_{uo2})+(a_{uw3},k_{uw3},k_{uo3})S),\\&k_u = const\end{aligned} \quad (3)$$

In (3) the constant coefficients have different values for the two sub-bands: S≤0.5% and S>0.5%.

The algorithm for determining volumes v_g, v_o, v_w for the given salinity comes to the solution of the system of equations (1), (2) and takes into account functions (3) and conditions (4) for three-component mixes

$$v_g + v_o + v_w = 1 \quad (4)$$

using the resonance frequency f and the amplitude of oscillations u measured by the resonance sensor. Solving this system in MathCAD for different v_g, v_o, v_w initial values within the limits of their possible existence, we find that the obtained solutions are unique.

4. TWO-COMPONENT STRATIFIED FLOWS

Stratification occurs in gas-liquid flows in the horizontal sections of the pipeline, when gas attempts to fill the upper part, and also in the mixes of two immiscible liquids, that tend to stratify.

4.1. Laminar medium: "dielectric - dielectric with the variable permeability and conductivity"

This electric model of the flow is common for industrial discharges in non-pressure pipelines in which a layer of gas is located in the upper part, and the lower part is filled with liquid with a variable dielectric permeability and conductivity, that is caused by variability of its composition. In this case, the effectiveness of measurements is determined by their invariance to the properties of the controlled media. To ensure the mentioned invariance, we proposed a method of obtaining the primary information in type 2 resonator. For the conduit, the cross section of the filled with liquid part of resonator is the segment with the height that varies depending on the filling (fig.3). Two fields are excited in the resonator: one with the vector of electrical tension $\overline{E}_1$ with the line of direction at angle α_1 to the surface of liquid, and another - with vector $\overline{E}_2$ with the line of direction at angle α_2 to this surface. Vectors $\overline{E}_1$ and $\overline{E}_2$, having arbitrary angles α_1 and α_2 can be decomposed on the components of vectors, $\overline{E}_{\shortparallel}$ and $\overline{E}_{\perp}$ correspondingly, parallel and perpendicular to the surface of liquid.

Substituting the indicated decomposition into the known formula for the natural frequency

$$f_i = f_{0i}((1+\int_V(\varepsilon-1)\overline{E}_i\overline{E}_{0i}dv) / \int_{V_0}\overline{E}_i\overline{E}_{0i}dv)^{-1/2}, \quad i=1,2$$

we obtain that natural frequencies are interconnected and have the following relationships:

$$1-(f_i/f_{0i})^2 = (a_1,b_1)(1-(f_\perp/f_{0\perp})^2 + (a_2,b_2)(1-(f_\parallel/f_{0\parallel})^2$$

Knowing dependences $f_{\|}$ and $f_{\perp}$ on the parameters of filling of the resonator: ε - dielectric permeability of liquid and $v_l = V/V_0$ - relative volume of filling (V - volume of the part, filled with liquid; V_0 - volume of the entire region of filling), from the measured frequencies f_1, f_2, f_{01}, f_{02}, it is possible to find the parameters of the filling indicated. To obtain the unique solutions, it is necessary that the sign of a difference in frequencies $f_1 - f_2$ should not change for any volume of the region of filling, and also $a_1 \neq b_1$, $a_2 \neq b_2$.

The excitation of such fields can be realized on the basis of the resonator with the locked zigzag conductor distributed inside the wall of the dielectric tube (type 2) via the connection of the generator to different points of the conductor, which do not lie on one element of cylinder. This type of resonator is used as the sensor of media parameter transducer for arbitrary dielectric permeability and conductivity.

In the special case, the invariance can be obtained by measuring resonance frequencies of two induced electromagnetic fields with mutually perpendicular electrical components that are placed relative to the surface of liquid as shown on Fig.3. The generator connected with the distributed conductor through the connecting element, induces one of these fields. The signal enters the detector from the opposite point of the conductor through the connecting element as well. Another pair of connecting elements moves to π/2 and together with the first pair and ensures induction of the required fields.

The functions of the resonance frequencies of the resonator for the corresponding fields (the process is similar to the fields in the capacitor) that were refined experimentally, take the following form:

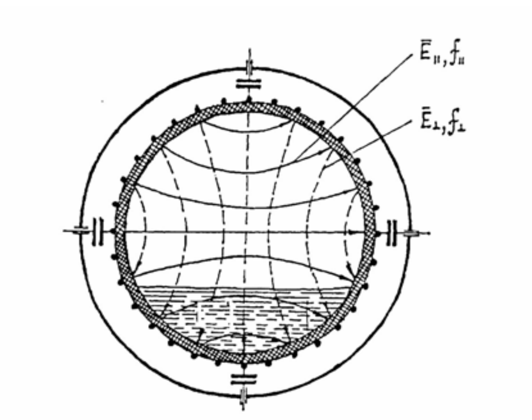

Fig.3. Configuration of two inter-perpendicular fields in the cross section of type 2 resonator

$$f_{\|}/f_{0\|} = \left(1 + (q-1)(v_l + v_l(1-v_l)(c_1\varepsilon + d_1))\right)^{-1/2} \quad (5)$$

$$f_{\perp}/f_{0\perp} = (1 + ((1/q) - 1)(v_l + v_l^2(1-v_l) \cdot ((1/c_2)\varepsilon + (1/d_2))))^{1/2} \quad (6)$$

where $f_{\|}/f_{0\|}$, $f_{\perp}/f_{0\perp}$ - are respectively natural frequencies of the sensor with parallel and perpendicular electrical field components to the boundary of the division of layers,

$$q(\varepsilon) = a\varepsilon + b \quad (7)$$

In these formulas a, b, c_i, d_i *–const*.

Using the system of equations (5,6) for the measured values of frequencies, it is possible to determine the true degree of filling v_l of the resonator with liquid for any unknown dielectric permeability. An error in the solutions, over a wide range of dielectric permeability from 2.2 (petroleum products) to 80 (water), does not exceed 2% if an error of the measurement of frequencies does not exceed 10^{-3}**.**

By analogy with section 3.1, we determined that the system of equations (5) and (6) has a single solution for v_l in the entire range of its change, within the limits of error indicated.

4.2. Algorithms of invariant measurements with the radio-frequency transducer of level

The task of determining the volumetric content in two-layer medium can be reduced to measurement of the level based on a resonator in the shape of the distributed section of a long line (Lunkin and et al; 2007*)*. The presence of the layer with conducting properties in the controlled medium determines the need for application of the insulation on at least one of the conductors that form the long line. The presence of an insulating shell makes it possible to limit the problem to the case when all layers are dielectrics with effective dielectric constants determined by the structure of the section of the long line and the insulating shell parameters. In this case, obtaining function $F = (f_0/f)^2 - 1$ on the degree of the filling with homogeneous medium with accuracy to the constant coefficient is ensured by the same configurations of the distribution of the long line, as for the line without the insulating shell (f_0 - resonance frequency of the long line, filled with the media with dielectric permeability of one of the layers, f is resonance frequency for two-layer medium).

Type 3 resonator, that consists of the two-wire circuit located above the metal strip, placed in the flat flexible insulator (1) can be used in pipelines. At one end of this strip the conductors (2) are connected, while on the other - each conductor is connected with the metal strip (3). This construction of a sensor is installed at the wall of the pipeline in such a way that the longitudinal axis of the tape is located in its cross section.

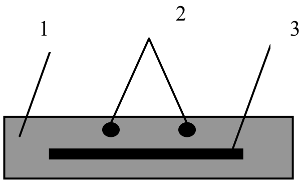

Fig. 4. Cross section of the band-type sensor (type 3)

The function of resonance frequencies f_i of this resonator that is calibrated to the appropriate resonance frequencies f_{oi} with $x=0$, to the level of filling x/l (x - length of the belt, immersed in the liquid, l - its overall length) can be written as

$$f_i/f_{0i} = \left[1 + k_i(\varepsilon - 1)\varphi_i(x/l)\right]^{-1/2} \quad (8),$$

where i is the number of resonance frequency, induced in the sensor, k_i - coefficient, determined by the parameters of insulator and external circuits, $\varphi_1 = x/l$ - the function, that is determined by the distribution of voltage along the conductor. For the given structure $\varphi_1 = x/l$, $\varphi_2 = (x/l) + (1/\pi)\sin(\pi x/l))$. As follows from these expressions, the result of the conversion of frequencies

$$A = (k_1/k_2)((f_{02}/f_2)^2 - 1)/(f_{01}/f_1)^2 - 1)) \quad (9)$$

is determined by the level of filling x/l and does not depend on the dielectric permeability of the controlled liquid. The relationship between the volumetric content of the lower layer and the degree of filling is established from the geometric ratios for a circle.

5. THREE-COMPONENT STRATIFIED FLOWS

The algorithms are based on the relationships between the measured values of the resonator and the volumes of the components of a mix. Obtaining such functions for three-layered flows is a complex electrodynamic task. A method of approximation, based on the results described in paragraph 4.1 for naturally stratified from top to bottom "gas - oil - water" flows, has been proposed.

5.1. "Gas - oil - water" medium

Using relationships (5), (6) for resonance frequencies, the expressions for the three-component medium take into account the possibility of existence of the following pairs of layers: "gas (g) – water (w)", "oil (o) - water", "gas-oil", and then

$$f_{||}/(f_{||})_{v_g=1} = (1 + (\overline{q}(\varepsilon_o/\varepsilon_g) - 1)v_o)^{-1/2}$$
$$\cdot(1 + (\overline{q}(\varepsilon_w/\varepsilon_g) - 1)(v_w + v_w(1 - v_w)(c_1(\varepsilon_w/\varepsilon_g) + d_1)^{-1/2} \quad (10)$$

$$f_\perp/(f_\perp)_{v_g=1} = (1 + ((1/\overline{q}(\varepsilon_o/\varepsilon_g)) - 1)v_o)^{1/2}$$
$$\cdot(1 + ((1/\overline{q}(\varepsilon_w/\varepsilon_g)) - 1)(v_w + v_w^2(1 - v_w) \quad (11)$$
$$\cdot(1/c_2(\varepsilon_w/\varepsilon_g) + d_2))^{1/2}$$

In these expressions c_1, c_2, d_1, d_2 are constant coefficients; $\overline{q}(\varepsilon_i/\varepsilon_j)$ - is a function of the ratio of the dielectric permeability of corresponding layers, that has to satisfy the following condition:

$$\overline{q}(\varepsilon_w/\varepsilon_g) = \overline{q}(\varepsilon_o/\varepsilon_g)\overline{q}(\varepsilon_w/\varepsilon_o) \quad (12).$$

The latter follows from the fact that for both natural frequencies $f_{v_w=1}/f_{v_g=1} = (f_{v_w=1}/f_{v_o=1})(f_{v_o=1}/f_{v_g=1})$ is true.

Furthermore, if the sensor is filled completely with one of the media, the following conditions of the equation of relative frequency of each of the fields to the values of these frequencies, obtained for the two-component flows, have to be satisfied:

$$(f_{||})_{v_g=1}/(f_{||})_{v_g=1} = (f_\perp)_{v_g=1}/(f_\perp)_{v_g=1} = 1,$$

$$(f_{||})_{v_o=1}/(f_{||})_{v_g=1} = (f_\perp)_{v_o=1}/(f_\perp)_{v_g=1}$$
$$= (\overline{q}(\varepsilon_o/\varepsilon_g))^{-1/2} = (q(\varepsilon_o/\varepsilon_g)^{-1/2} \quad (13),$$

$$(f_{||})_{v_w=1}/(f_{||})_{v_g=1} = (f_\perp)_{v_w=1}/(f_\perp)_{v_g=1}$$
$$= (\overline{q}(\varepsilon_w/\varepsilon_g))^{-1/2} = (q(\varepsilon_w/\varepsilon_g))^{-1/2} \quad (14).$$

These conditions can be carried out, for example, for the following function: $\overline{q}(\varepsilon_i/\varepsilon_j) = m(\varepsilon_i/\varepsilon_j)^2 + n(\varepsilon_i/\varepsilon_j) + pq(\varepsilon_i/\varepsilon_j)$, in which $q(\varepsilon_i/\varepsilon_j)$ is taken from the formula (7). After solving (12), (13) and (14) we obtain the values of m, n, p, reduce equations (10), (11), and determine the volumes of the layers, taking (4) into account.

The uniqueness of the obtained solutions for the volumes follows from the uniqueness of the solutions of system of equations (5) and (6).

5.2. Algorithm that is based on detectors of position of layer boarders

The possibility to measure the position of boarders of layer distribution of " dielectric – dielectric - dielectric with variable conductivity" type model is shown (Lunkin and Kriksunova, 2007). The same model can be used for “gas – oil – water” mixes, that are stored in reservoirs: water is accumulated in the lower part (usually water obtains its conducting properties due to the salt content), oil (petroleum products) – in the middle part, gas (both oil and gas are dielectrics) – in the upper part. Two distributed sections of a long line in the insulating shell with different functions of filling *F* (see division 4.2) are used as a sensor: one realizes linear function, and the other - quadratic. They make it possible to form a system of equations for determining the position of boarders using the measured resonance frequencies. When applied to the flow of three-layered medium with the same model of distribution of layers, in which their volumetric content is determined by the degree of filling of the strip-type resonator (type 3), fixed on the wall of the pipeline, the mentioned system of equations takes the following form:

$$\begin{cases}(a_1 + b_1 F_1)\bar{x}_w + c_1 \bar{x}_o = F_1 \\ (a_2 + b_2 F_2)\bar{x}_w^2 + c_2 \bar{x}_o^2 = F_2\end{cases},$$

where $\bar{x}_{w,o} = x_{w,o}/l$ - the end-points of filling of the section of flexible tape, correspondingly, by water and by oil. Let us note that coefficients a_i, c_i are proportional to $\varepsilon_w, \varepsilon_o$ respectfully. Experimental results confirm the correspondence of the solutions of this system: the obtained error in determining the position of boarders does not exceed 3.0% with 10^{-3} accuracy of the measurement of frequency. However, for some values of frequencies, as it was expected, the presence of another solution is noticed.

Similarly, the functions of the first resonance frequencies of the sensor, which consists of two sections of the long line with different thicknesses of insulating shells with linear functions *F*, form the system of linear equations:

$$(a_i + b_i F_i)\bar{x}_w + c_i \bar{x}_o = F_i, \quad (i = 1,2) \qquad (15).$$

By expressing the coefficients through dielectric permeability of the layers and the shell parameters, we are able to demonstrate that the system has a single solution when resonance frequencies are not equal. The latter is always true for the sections of line with different shell thicknesses.

Each section of the line is structured on the model shown on Fig. 4, but it has only one conductor, one end of which is short-circuited with a metal strip, and the other is disconnected. Experimental results show that an error in determining the position of the boarders of medium of the "gas – oil - water" type, expressed by the degree of filling of sections of the long line with medium of each layer, does not exceed 2.0-2,5% when the error of measurement of resonance frequency does not exceed 10^{-3}. Volumetric content of each layer is determined by the degree of filling from the appropriate formulas for a circle.

REFERENCES

Lunkin, B.V., V.I. Mishenin, N.A. Kriksunova and V.Ia.Fateev (1999). New developments of radiofrequency transducers. *Sensors and systems*, №2, p. 43-48.

Lunkin, B.V. and N.A. Kriksunova (2007). The determination of the position of the interfaces of laminar media with the aid of the radio-frequency sensor. *Sensors and systems*, №1, p. 8-12.

Lunkin B.V., V.I. Mishenin and N.A. Kriksunova (2007). The principles of the construction of the radio-frequency sensors of fluid flow rate in the non-pressure channels for the systems of ecological monitoring. In: *The proceeding of science conf. Automation into Manufacturing*. Moscow. Institute of Control Sciences. ISBN 5-201.

Wylie, S.R., A. Shaw and A.I. Al-Shamma’a (2006). RF sensor for multiphase flow measurement through an oil pipeline. *Meas. Sci. Technol.* 17, №8, p. 2141-2149.